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Request for grant of a patent

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Cardiff Road
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1. Your reference	AMS.P52652GB	
2. Patent application number *(The Patent Office will fill in this part)*	26 MAR 2003	0306920.0
3. Full name, address and postcode of the or of each applicant *(underline all surnames)*	WesternGeco Seismic Holdings Limited Citco Building PO Box 662 Road Town Tortola British Virgin Islands	
Patents ADP number *(if you know it)*		8472177001
If the applicant is a corporate body, give the country/state of its incorporation	British Virgin Islands	
4. Title of the invention	"Processing Seismic Data"	
5. Name of your agent *(if you have one)*	Marks & Clerk	
"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*	4220 Nash Court Oxford Business Park South Oxford OX4 2RU United Kingdom	
Patents ADP number *(if you know it)*	7271125001	

6. If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and *(if you know it)* the or each application number	Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*

7. If this application is divided or otherwise derived from an earlier UK application, give the number and the filing date of the earlier application	Number of earlier application	Date of filing *(day / month / year)*

8. Is a statement of inventorship and of right to grant of a patent required in support of this request? *(Answer 'Yes' if:* *a) any applicant named in part 3 is not an inventor, or* *b) there is an inventor who is not named as an applicant, or* *c) any named applicant is a corporate body.* *See note (d))*	Yes

9. Enter the number of sheets for any of the following items you are filing with this form. Do not count copies of the same document

Continuation sheets of this form	0
Description	6
Claim *(s)*	0
Abstract	0
Drawing *(s)*	5 + 5

10. If you are also filing any of the following, state how many against each item.

Priority documents	
Translations of priority documents	
Statement of inventorship and right to grant of a patent *(Patents Form 7/77)*	
Request for preliminary examination and search *(Patents Form 9/77)*	
Request for substantive examination *(Patents Form 10/77)*	
Any other documents *(please specify)*	

11. I/We request the grant of a patent on the basis of this application.

Signature Mark a Clerk Date

Marks & Clerk 25 March 2003

12. Name and daytime telephone number of person to contact in the United Kingdom

Dr Andrew Suckling
(01865) 397900

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c) If there is not enough space for all the relevant details on any part of this form, please continue on a separate sheet of paper and write "see continuation sheet" in the relevant part(s). Any continuation sheet should be attached to this form.
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Processing Seismic Data

The present invention describes the recording of acceleration seismic data at the seafloor, on land and in the borehole, and the processing of acceleration data to provide enhanced resolution of sub-surface images for the elastic wavefield.

The task of seismic recording and processing is to image subsurface structures. The quality of the images depends on the frequency range of the seismic waves recorded by the seismic acquisition system. Figure 1 shows the importance of high frequencies for the quality of the subsurface seismic image. Broad structures like those labelled "B" do not suffer significantly from low frequency recording. Finely structured events like those labelled "A", however, are not resolved by the low frequency image on the left, whereas the high frequency image on the right clearly shows all details of the structure. Also distinctive events like faults labelled "C" show degradation in delineation as a result of low frequency recording.

Sea-floor and land seismic data acquisition systems use geophones to measure the incident seismic wavefield. Geophones are regarded as velocity sensing devices. The seismic industry has used such velocity sensing geophones for many years and it has become accepted that the images we produce of the subsurface structures are effectively measures of the velocity wavefield.

With the advent of the acceleration sensors in the seismic industry (GAC – Schlumberger geophone accelerometer, Vectorseis – I/O accelerometer and GeoSil - Schlumberger acceleration seismic sensor), we have the opportunity to record and process acceleration data instead of velocity data. Acceleration sensors are more sensitive to higher frequencies when compared with velocity sensors as shown in figure 2. Therefore acceleration sensors are preferred for high-resolution seismic imaging.

Schlumberger first used the GAC sensor (disclosed in JP06027135 A and WO0218975 A1) in the early 1990's for vertical seismic prospecting in the borehole, while I/O have operated experimental land seismic crews using their VectorSeis sensor for a few years.

Both companies always transform their acceleration data to velocity data before proceeding to data processing. It has been assumed that the industry must accept only velocity equivalent data. This aids in comparison to legacy data acquired earlier using conventional velocity sensitive geophones. It also reflects the tendency in both borehole and land seismic data acquisition to assume that velocity measurements provide data with the broadest signal bandwidth with the flattest spectrum, giving the most reliable seismic data wavelets for interpretation.

U.S. Patent No. 4,951,264 is directed to a method of measuring the shear modulus profile of a seabed floor using one or more bottom shear modulus profilers, each having a seismometer package to measure seabed motion in three dimensions. The seismometers provide bed velocity or acceleration data. The acceleration data may be processed by various data processing algorithms, with the basic goal of spectral averaging.

U.S. Patent No. 4,807,199 is directed to a passive means of measuring the shear modulus profile of a seabed floor using gravity waves found in the sea. It describes using three seismometers to provide bed velocity or acceleration data. Signals of seabed motion velocity are used to determine the shear modulus profile.

U.S. Patent No. 5,268,878 is directed to an accelerometer sensor having a reduced periodic noise at a first frequency.

US Patent No. 6,430,105 discloses a multi component seismic sensor which utilises orthogonal accelerometers to determine its orientation.

WO0055646 discloses a method of operating and testing a sensor assembly that includes accelerometers with axes of sensitivity orthogonal to each other. The method preferably includes determining sensor tilt angle, determining the position of the sensor, and synchronizing the operation of the sensor.

WO0055638 describe a seismic sensor design and process for measuring acceleration data.

The present invention provides a method of processing seismic data representative of the acceleration wavefield thereby to obtain information about the earth's subsurface direct from the seismic data representative of the acceleration wavefield. The prior art step of converting the acceleration data to velocity data is not required.

Preferred embodiments of the present invention will now be described with reference to the accompanying figures in which:

Figure 1 is a comparison of a low-frequency image and a high frequency image of the earth's subsurface;
Figure 2 is a comparison of the output spectra for a velocity sensor and an acceleration sensor;
Figure 3 shows the low pass filter effect of the earth on a seismic signal;
Figure 4 shows the effect of acceleration recording on the frequency bandwidth of seismic data;
Figure 5 shows the effect of acceleration domain recording and processing on signal dynamic range;
Figure 6 shows spectra of sea-floor seismic data using velocity sensitive recording sensors;
Figure 7 is a schematic illustration of a towed marine seismic surveying arrangement;
Figure 8 shows typical amplitude spectra in a towed marine seismic surveying arrangement; and
Figure 9 is a comparison between processing of velocity data and acceleration data.

At the sea-floor, on land and in the borehole, the seismic energy emitted by the seismic source is broadband with a flat spectrum in the velocity domain. For the rejection of noise usually a band pass filter is applied with typical cut-off frequencies at 3 – 5 Hz for low frequencies and 60 to 120 Hz for high frequencies.

On its path through the subsurface the seismic wave is attenuated where the attenuation of high frequencies increases with offset as can be seen in figure 3. In essence the earth acts as a low pass filter for seismic data thus reducing the resolution of the final image of the subsurface.

The present invention recognises that for sea-floor, land and borehole seismic data measurements of the acoustic and elastic wavefields, acceleration measurements provide data with the desired flattest spectrum. This is because the higher frequency sensitivity of the accelerometer compensates for the low frequency domination of the energy from the seismic source. It is further claimed that we should proceed in processing the recorded acceleration wavefield to yield higher resolution images of the sub-surface than could be found from processing of velocity data as shown in figure 4. Such a scheme would avoid the damaging early transformation from acceleration to velocity in the processing flow.

When considering the dynamic range of the data used for subsurface seismic imaging the noise has to be considered as well. Noise manifests in seismic data in two ways :

- system quantisation noise, from which no signal can be recovered,
- ambient noise, from which signal may be recovered during the data processing.

Only the representation of the ambient noise level increases when recording acceleration instead of velocity as shown in figure 5.

At the sea-floor and in borehole seismic data acquisition in the marine environment, the seismic energy emitted into the earth has a spectrum biased towards the low frequencies when recorded with a velocity sensitive geophone, as can be seen in figure 6. While the signal to noise ratio of the data is good across a considerable bandwidth of the data, most of the seismic energy is below 50Hz and exhibits a gradient dipping towards high frequencies.

Part of the reason is that the marine seismic source was designed and tuned to deliver seismic reflection data with as flat a spectrum as possible for towed streamers, where pressure sensing devices are towed some 6 metres or so beneath the water surface.

Towed streamer acquisition applies two ghost operators to the recorded seismic data, as can be seen in figure 7 – one from the seismic source and another from the seismic sensing receiver. Each application of such a ghost operator applies a notch filter at a high frequency that is dependent on either the source or receiver depth, and also a low cut filter at 0Hz. For the towed marine configuration, we therefore apply two low frequency filters to the data, giving the finally recorded data a flatter spectral appearance, as seen in figure 8.

At the sea-floor and in the borehole for marine acquisition, we only have one low cut filter applied to the data from the source ghost. The receiver ghost does not apply because our recordings are made either at the sea-floor or in the borehole. Thus, we do not apply a second low cut filter to our final data. Consequently, such sea-floor and borehole marine seismic data become biased towards low frequencies and are deficient in high frequencies.

Accelerometers are more sensitive to high frequency signals than low. So acceleration measurements at the sea-floor or in the borehole will provide data with the desired flattest spectrum. This is because the higher frequency sensitivity of the accelerometer compensates for the low frequency domination of the energy from the seismic source.

The processing flow for acceleration data needs to take care of the attenuation of the relatively higher ambient noise level at higher frequencies. Figure 9 shows typical data flows for velocity and acceleration domain processing of seismic data. The low pass filtering of velocity data can not be compensated during processing and consequently results a in lower frequency and lower resolution seismic image of the subsurface. The low pass filtering of acceleration is partly compensated for by the recording of acceleration. The resulting higher levels of ambient noise need to be corrected for in a dedicated step during processing. Point source – point receiver based noise attenuation is well suited for this task.

The present invention provides the recording and processing of acceleration data to produce higher bandwidth seismic images with higher resolution than the conventional velocity data.

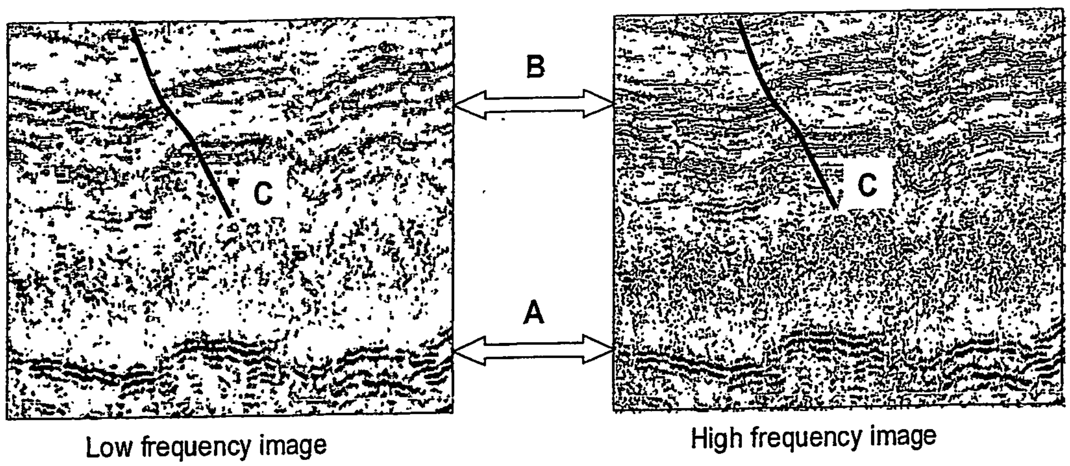

Figure 1 - Importance of frequency in seismic records : Events A are not resolved in the low frequency image

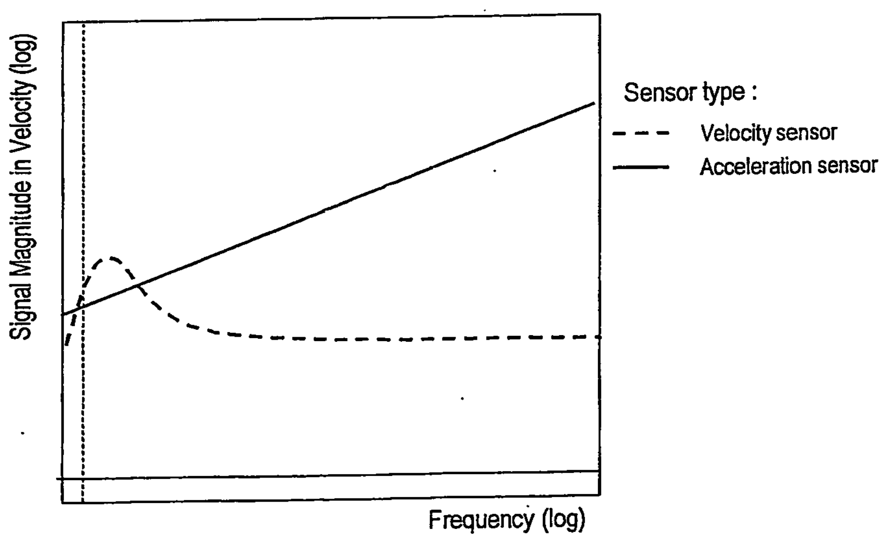

Figure 2 - Comparison of the output spectrum of velocity and acceleration sensors. For comparison the frequency response is plotted in the velocity domain.

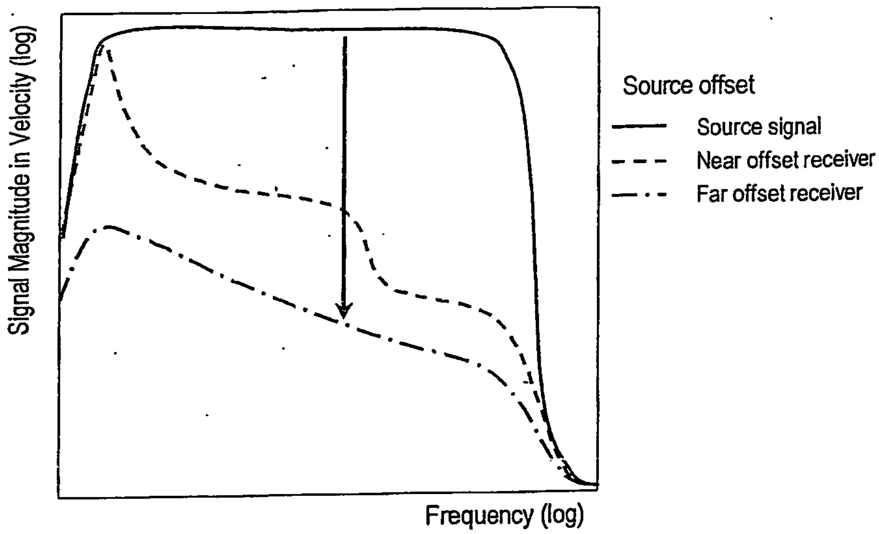

Figure 3 - Low pass effect of the earth between source and receiver

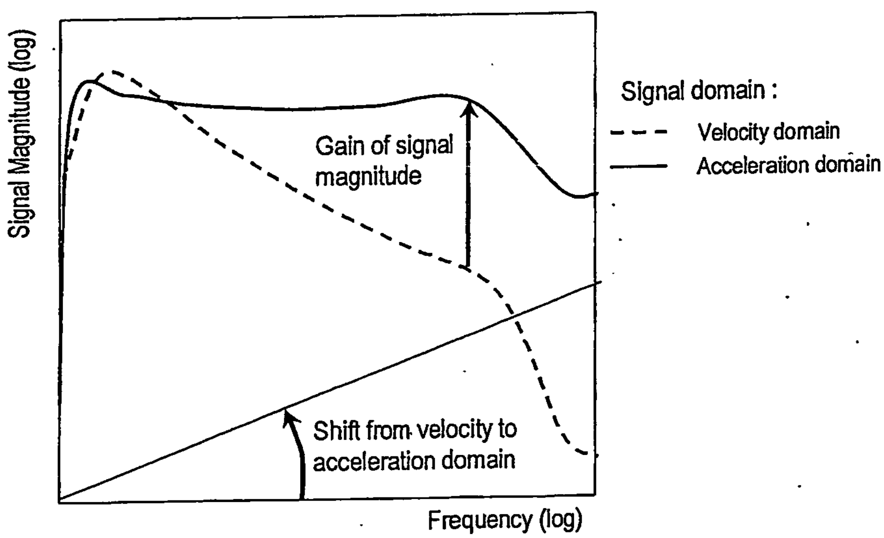

Figure 4 - Effect of acceleration recording on the frequency bandwidth of seismic data

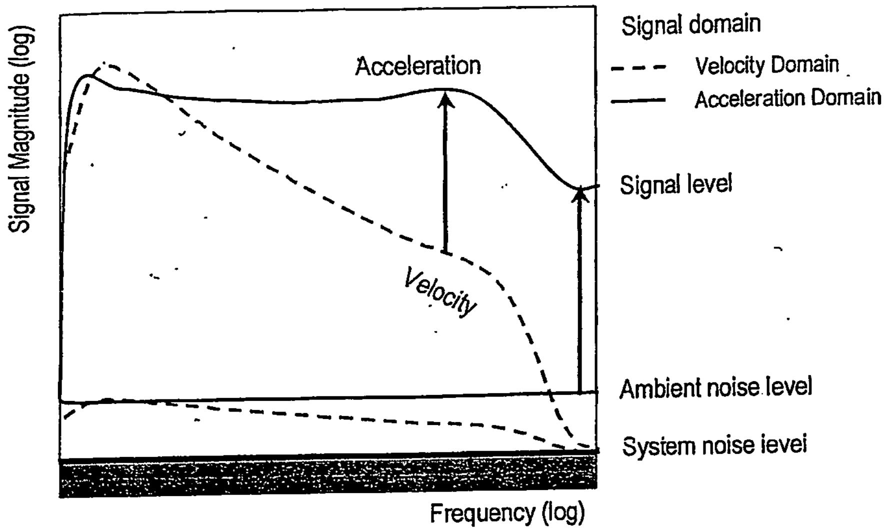

Figure 5: Effect of acceleration domain recording and processing on signal dynamic range

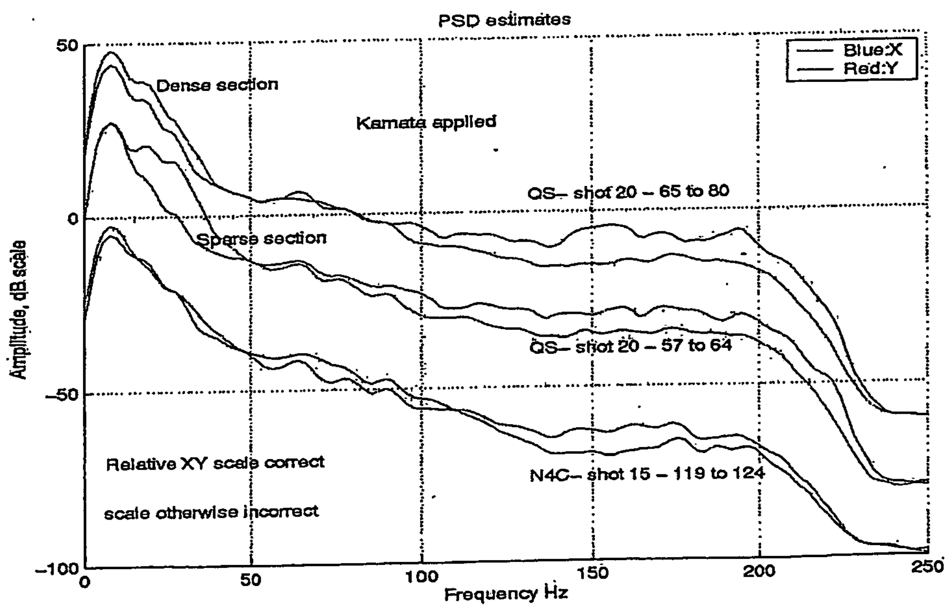

Figure 6: Spectra of sea-floor seismic data using velocity sensitive recording sensors, showing undesired bias towards low frequency signal.

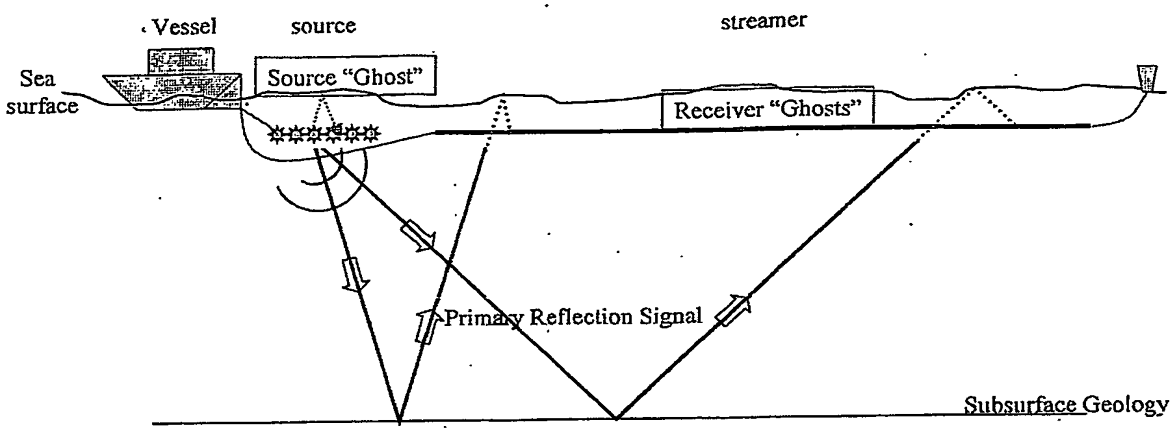

Figure 7: Schematic showing towed streamer seismic data acquisition, with undesired source and receiver ghost events, which introduce replications of the desired primary seismic data with short propagation time delays.

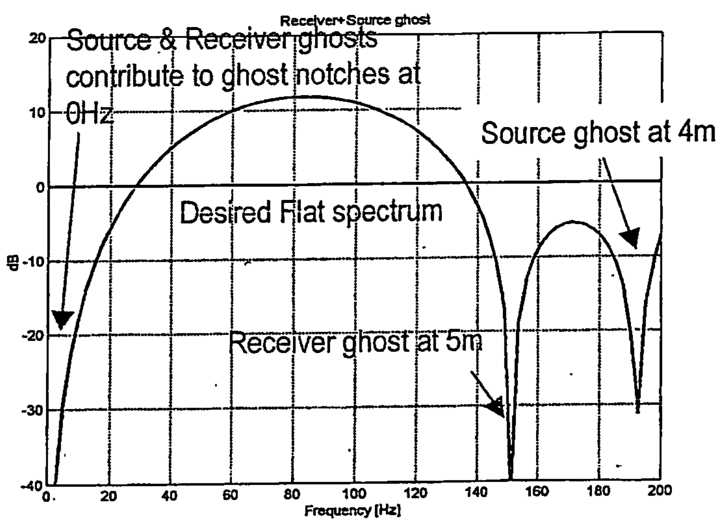

Figure 8: Amplitude spectrum showing how the source and receiver ghosts from towed marine seismic data acquisition introduce spectral notches at higher frequencies, and how they both contribute to the spectral notch at 0Hz.

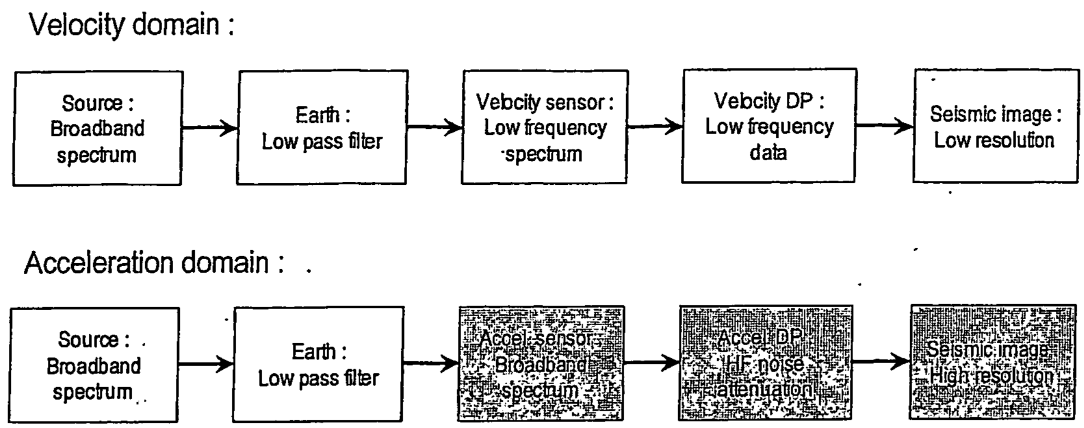

Figure 9: Data flow for velocity and acceleration seismic data

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